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HIGH-INTENSITY BEAM DYNAMICS SIMULATION OF THE IFMIF-LIKE ACCELERATORS

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Abstract

The IFMIF (International Fusion Material Irradiation Facility) project is being considered to build fusion material test facility. The IFMIF will use two accelerators to generate high energy neutrons. However, the IFMIF accelerators have been designed to have much higher beam power and beam current than the existing accelerators, so space charge effect is very strong. This raises big concerns about beam loss and beam transport stability, thus detailed high-intensity beam dynamics study of the IFMIF-like accelerators is indispensable. This research aims to perform source to target simulation of the IFMIF-like accelerator. The simulation has been carried out by two different kinds of simulation codes because the IFMIF accelerator has distinctive features. One is TRACEWIN simulation code which was used in IFMIF initial design. The other is WARP 3D PIC code which can precisely calculate space charge effects.

INTRODUCTION

The IFMIF accelerator accelerates D^+ with 125 mA beam current. The high beam current makes strong space charge effect and it derives serious concern about beam transport stability. Therefore, beam dynamic study must be handled carefully. We do simulation for LEBT and MEBT of IFMIF-like beam line. Both LEBT and MEBT simulations are done by WARP and TRACEWIN simulation codes.

Simulation Code

Two kinds of simulation codes are used in simulation. One is WARP which was developed by LBNL. Calculation algorithm of the WARP is PIC (Particle in Cell). Therefore, it can precisely simulate space charge effect. The other one is TRACEWIN which was made by CEA – Saclay. It uses second order momentum and macroparticle in simulation.

Low Energy Beam Transport

Basically, LEBT consists of ECR ion source, two solenoids and RFQ injection cone. ECR ion source makes D^+ beam with 0.064 π mm. mrad emittance and 100 keV beam energy.

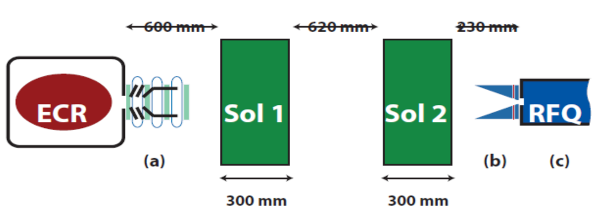

Figure 1: Schematic of IFMIF LEBT [1].

Figure 1 shows the schematic of IFMIF LEBT. In more detail, beam pipe radius is 80 mm and becomes smaller at RFQ injection cone. Radius of RFQ injection cone is 35 mm at entrance and 12 mm at exit. Magnetic field strength of solenoid 1 is 0.37 T and 0.47 T for solenoid 2. LEBT aims to make a beam with 0.233 π mm. mrad emittance at the exit of LEBT. To achieve the goal, IFMIF LEBT uses SCC (Space Charge Compensation).

Space Charge Compensation

Space charge compensation which will be written as SCC in this paper is one of methods to reduce space charge of beam. It uses residual gas to reduce space charge effect.

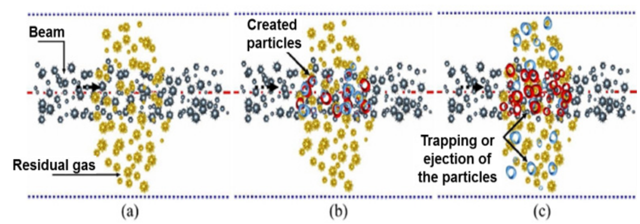

Figure 2: Outline of Space Charge Compensation [2].

Figure 2 shows the outline of space charge compensation. As shown in Fig. 2, beam particles interact with residual gas and they make ions. Ions which have the same charge type as the beam are propelled from beam, whereas ions which have different charge type with the beam are trapped to beam. The trapped ions (or electrons) reduce space charge of the beam. SCC needs time for stabilization which is also called as neutralization time written as Eq. (1):

$$\tau_n = \frac{1}{n_g \sigma_i v_b}, \tag{1}$$

Where n_g is gas density in beam line, σ_i is ionization cross section of beam-residual gas interaction, and v_b is velocity of beam particle. In this study, neutralization time is 6 μs.

Medium Energy Beam Transport

MEBT aims to manipulate beam before beam goes into SRF (Super Conducting Radio Frequency) beam line.

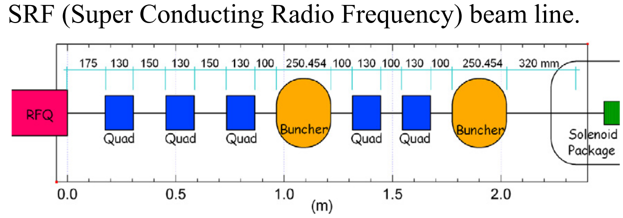

Figure 3: Schematic of IFMIF MEBT [3]

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As shown in Fig. 3, the length of MEBT is about 2 m. It consists of triplet, doublet, and two bunchers. In the simulation, magnetic gradients of quadrupole 1, 2, and 3 are 25 T/m, and 20.5 T/m for quadrupole 4 and 20 T/m for quadrupole 5. Buncher frequency is 175 MHz and maximum E_0LT value for buncher is 350 kV.

LEBT SIMULATION

LEBT simulation has been done for 2 different cases. One is 'Without SCC case' and the other is 'With SCC case'. Those two cases are simulated in both WARP and TRACEWIN.

Table 1: Initial Beam Parameters (LEBT) [1]

Beam Parameter	Initial Value
Beam Current	125 mA
Beam Energy	100 keV
Normalized Emittance	0.064 π.mm.mrad
Twiss Parameter	α:0.8, β: 2.0

Table.1 is about initial beam parameters for LEBT simulation. Beam parameters are those of IFMIF except the Twiss parameters.

Without SCC

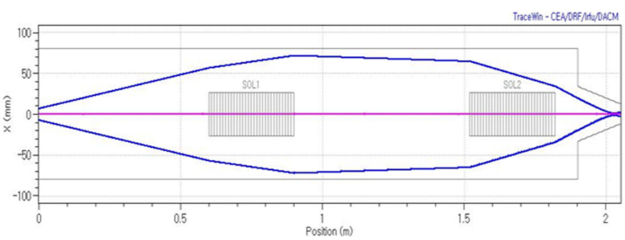

Figure 4: Z–X Plot from TRACEWIN (Without SCC).

As shown in Fig. 4, maximum envelope radius is almost 80 mm and maximum rms radius is around 35 mm. Also normalized emittance is 0.2796 π mm. mrad at the exit of LEBT.

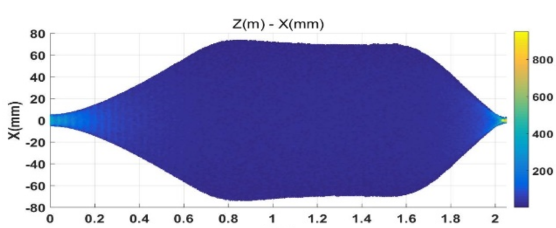

Figure 5: Z–X Plot from WARP (Without SCC).

Figure 5 is plot for WARP simulation. WARP simulation shows similar result with TRACEWIN simulation. Maximum envelope radius is almost 80 mm and maximum rms radius is around 40 mm. Normalized emittance is 0.3697π mm. mrad . It is a little bit bigger than TRACEWIN result.

In both WARP and TRACEWIN simulations, calculated normalized emittances are much higher than our target value. Also, maximum beam envelope is around 80mm, so beam loss is concerned in real experiment.

With SCC

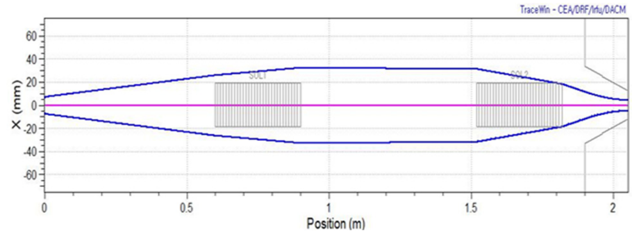

Figure 6: Z–X Plot from TRACEWIN (With SCC).

TRACEWIN simulation is done with compensation factor of 0.75. Maximum beam radius is around 35 mm. Maximum rms radius is around 16 mm and normalized emittance at the exit of LEBT is 0.1228 π mm. mrad which satisfies the target value.

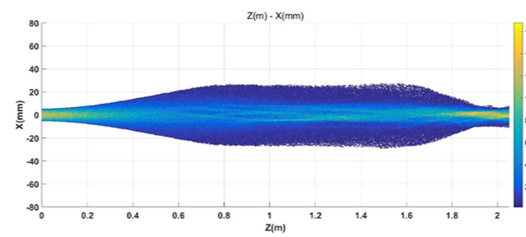

Figure 7: Z–X Plot from WARP (With SCC).

WARP simulation doesn't use compensation factor, but instead it uses full atomic processes. Therefore, Figures 6 and 7 show a little difference. Maximum beam radius in WARP simulation is around 30 mm which is smaller than TRACEWIN value. From the WARP, maximum rms radius is around 10 mm and normalized emittance is 0.1763 π mm. mrad at the exit of LEBT. However, instability was observed in the WARP simulation

Instability Issue

Only WARP supports full atomic processes and it makes some difference between TRACEWIN and WARP simulation results. One of the difference is instability. Instability was observed only in WARP simulation.

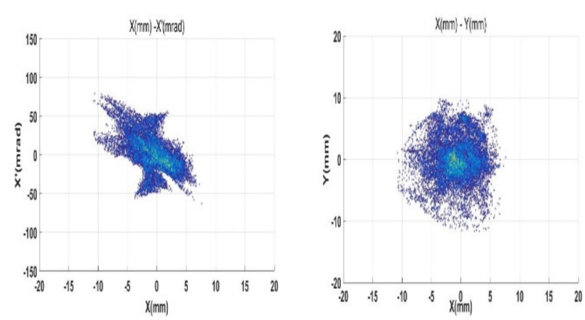

Figure 8: X–X' (left) and X–Y (right) at LEBT exit.

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In Fig. 8, tail shape has appeared, and beam shape collapsed. The cause of instability is not clear yet, but we suspect that it is a kind of two stream instability.

MEBT SIMULATION

Table 2: Initial Beam Parameters (MEBT) [4]

Beam Parameter	Initial Value
Beam Current	125 mA
Beam Energy	4.98 MeV
longitudinal Emittance	0.3 π.mm.mrad
Twiss Paramter	α X : -1.95, β X : 0.37 α Y : 1.5, β Y : 0.355

Table.2 is about initial beam parameters of MEBT simulation. Beam parameters for MEBT simulation are those of IFMIF except the Twiss parameter. Twiss parameters are optimized values obtained from our simulation.

Simulation Results

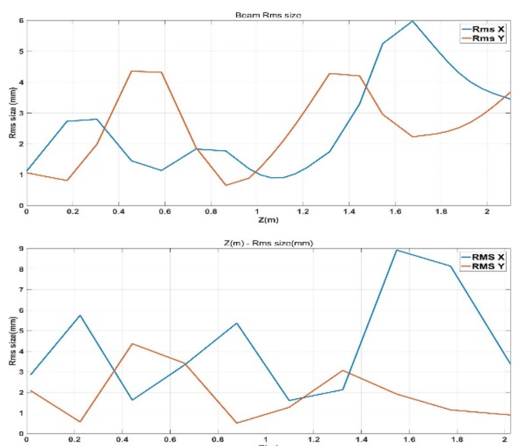

Figure 9: RMS X, Y (top: TRACWIN, bottom: WARP).

Figure 9 shows RMS radius history in TRACEWIN and WARP. Tendency of TRACEWIN and WARP is similar for rms x value. At MEBT exit, rms x value is 8 mm at TRACEWIN and 7.5 mm at WARP. However, rms y value becomes different after second buncher. WARP roughly supports RF lattice so we use time varying electric field in WARP simulation instead, which seems to make such difference. Optimization is one of the future plans.

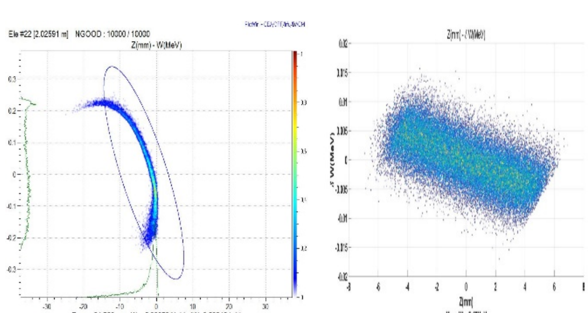

Figure 10: Z–Energy (left: TRACEWIN, right: WARP).

Buncher gives kick to beam, in such way that particles at tail of the bunch become faster so it makes velocity bunching. At MEBT exit rms z value is around 3 mm in both TRACEWIN and WARP. However, as we can see in Fig. 10, phase diagrams are different between two codes, so further optimization and comparison will be done in future.

Peak Current Issue

Average beam current of IFMIF accelerator is 125 mA and operation type is CW. After RFQ, continuous beam becomes bunched and the peak current will be higher than 125mA. Therefore, we do simulation with higher current for MEBT simulation.

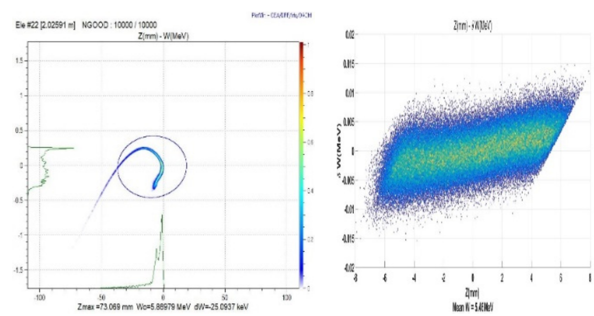

Figure 11: Z- Energy with 375mA peak current (left: TRACEWIN, right: WARP).

The simulation is done with 375 mA peak current case. As shown in Fig. 11, the buncher fails to make velocity bunching because of the stronger longitudinal space charge. Bunch length become larger even we use buncher to suppress bunch length growth.

CONCLUSION & FUTURE PLAN

Space Charge Compensation is an essential tool in IFMIF LEBT beam line. If we don't use SCC in IFMIF LEBT, serious beam loss may occur. Furthermore, without SCC, normalized emittance is higher than target value. We can achieve the normalized emittance goal only when we use SCC.

MEBT works well for the nominal beam conditions but if peak current becomes higher, it doesn't work well. The simulation case presented here is one of the extreme cases; nonetheless we note bunchers of the MEBT need to be designed with margin.

Instability has been observed in the LEBT WARP simulation. Finding the cause of the instability or optimization of the LEBT WARP simulation will be carried out as future works.

In MEBT simulation, different features exist between TRACEWIN and WARP results. It is likely caused by RF lattice setting in the WARP simulation. It should also be optimized in the future.

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